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TRANSLATION

TAKING INTO ACCOUNT THE MOLECULAR COMPOSITION OF AIR IN CALCULATIONS OF AERODYNAMIC FORCE COEFFICIENTS AND BODY TEMPERATURE IN FREE-MOLECULE FLOW AT HIGH SUPERSONIC VELOCITIES

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TAKING INTO ACCOUNT THE MOLECULAR COMPOSITION OF AIR IN CALCULATIONS OF AERODYNAMIC FORCE COEFFICIENTS AND BODY TEMPERATURE IN FREE-MOLECULE FLOW AT HIGH SUPERSONIC VELOCITIES

V. S. Galkin

In the mechanics of a continuous medium when there are no chemical reactions, a mixture of gases is considered as a single-component gas with an average value of the molecular weight, specific heat, etc. For free molecular flow, this corresponds to introducing a single distribution function for the gas mixture with the same temperature, average mass density, and average molecular weight μ. The aerodynamic coefficients and energy flows obtained in this way will be denoted by appropriate subscripts with a superscript of 0 (e.g., a drag coefficient c_x^0, etc.). In reality such a consideration is, generally speaking, incorrect. Actually the distribution function in a free molecular flow is the sum of Maxwell's distribution functions of the separate components of the gas. The mass, momentum, and energy flows are calculated separately for each component of the gas and then the results are added. Because of this, it is natural to assume that the quantities c_y^0, c_x^0, etc. may differ appreciably from their true values.

The obvious exception is the case of free molecular flow past bodies, whose angle of inclination θ of the surface to the direction of the high supersonic macroscopic velocity V_∞ is greater than 0. Then the thermal velocities of the molecules impinging on the body can be neglected in comparison with V_∞, and it may be assumed that the molecules travel parallel to each other with velocity V_∞ right up to collision with the surface.

For diffuse reflection and an accomodation coefficient $d \sim 1$, the momentum component of the reflected molecules parallel to $\vec{V}_\infty$ is negligible in comparison to the momentum of the oncoming flow $\rho_\infty V_\infty^2 \sin\theta\, ds$, per surface element ds. Therefore the drag coefficient of a surface element ds is $2 \sin\theta$ regardless of whether the gas is single-component or multicomponent, i.e., $C_x = C_x^o$.

Analogously the kinetic energy flow of the molecules impinging on the body is $E = E^o$. Since in this case the internal energy flow of these molecules is negligible in comparison with E^o, the total energy flow of the molecules impinging on the body is $W \approx W^o \approx E^o$.

As opposed to drag, lift in a free-molecule flow with a high supersonic velocity is caused not by the momentum of the oncoming stream, but by the momentum of the reflected molecules. In this case $C_y^o \sim \frac{1}{S}$, where the criterion S is the ratio of the velocity V_∞ to the most probable velocity $c = \sqrt{\frac{2R_0T_\infty}{\mu}}$. Here R_o is the absolute gas constant; the average molecular weight $\mu = \frac{\Sigma N_i\mu_i}{\Sigma N_i}$ and μ_i and N_i are the molecular weight and concentration of the i-th component of the mixture.

In the case of a two-component mixture [1]

$$C_y \sim \frac{1}{V_\infty}\left[\sqrt{\frac{2R_0T_\infty}{\mu_1}}\,\frac{\mu_1N_1}{N_1\mu_1+N_2\mu_2}+\sqrt{\frac{2R_0T_\infty}{\mu_2}}\,\frac{N_2\mu_2}{N_1\mu_1+N_2\mu_2}\right].$$

where $\frac{N_i\mu_i}{N_1\mu_1 + N_2\mu_2}$ is the ratio of the density of the i-th component to the density of the mixture.

Introducing $S = \frac{V_\infty}{\sqrt{\frac{2R_0 T_\infty}{\mu}}}$, $\overline{N} = \frac{N_2}{N_1}$ and $\overline{\mu} = \frac{\mu_2}{\mu_1}$, we obtain:

$$C_y \sim \frac{1}{S} \sum \frac{\mu}{\mu_i} \frac{N_i\mu_i}{N_1\mu_1 + N_2\mu_2} = \frac{1}{S} \frac{1 + \sqrt{\overline{\mu}}\,\overline{N}}{\sqrt{(1+\overline{N})(1+\overline{\mu}\overline{N})}} = \frac{\alpha}{S}.$$

A graph of α plotted against $\overline{\mu}$ for various $\overline{N}$ is presented in Fig. 1.

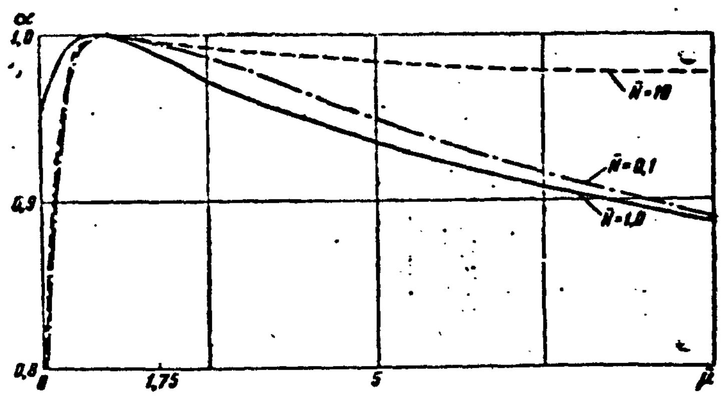

Fig. 1.

A regime of free-molecule flow past satellites and rockets occurs at altitudes $H \gtrsim 150$ km. In the range 150 km < H < 400 km the air consists of monoatomic oxygen ($\mu_1 = 16$) and diatomic nitrogen ($\mu_2 = 28$). At altitudes $H \gtrsim 400$ km the atmospheric gas is mainly monoatomic oxygen. Thus, in the range 150 km $\lesssim H \lesssim$ 400 km, $\overline{\mu} \approx 1.75$ and $\overline{N} \lesssim 1$. For this value of $\overline{\mu}$ we have $0.99 \lesssim \alpha \lesssim 1$, with α attaining a minimum when $\overline{N} \approx 1$.

Consequently, since $\overline{\mu}$ is sufficiently close to unity at high altitudes, it is possible to set $\alpha = 1$ and $C_y = C_y^0$ with an accuracy to 1%. We shall again stress that in the general case C_y may be considerably less than C_y^0.

It remains to investigate the flow past a surface set at zero angle of attack, when the effect of the multicomponent nature of the gas may also be large. In this case the influx of the mass, momentum,

and energy of the molecules against the surface is proportional to the mean thermal velocity of the molecules.

For example the kinetic energy flow

$E \sim C_1 \frac{\mu_1 N_1 V_\infty^2}{2} + C_2 \frac{\mu_2 N_2 V_\infty^2}{2}$. Analogously $E^0 \sim C \frac{\mu (N_1 + N_2) V_\infty^2}{2}$. Hence it follows that $E/E^0 = \alpha$. Analogously [1] $\frac{C_{x_0}}{C^0_{x_0}} = \alpha$ (the latter for any S). Consequently by virtue of the reasons set forth above, $C_{x_0} = C^0_{x_0}$ and $E = E^0$ with an accuracy to 1% (as soon as $\bar{\mu} = 1.75$).

Thus, assume a high flight velocity ($S \gtrsim 10$) and a flight altitude $H \gtrsim 150$ km. Then, on calculation of the aerodynamic forces and the kinetic energy flow of the particles inpinging on the body, the air may be considered as a single-component gas with the same density, temperature, and average molecular weight. In addition, calculations have shown that this conclusion is also valid with an accuracy to ~ 3% for moderate flight velocities $S \gtrsim 1$. It is also easy to show that these conclusions regarding the calculation of aerodynamic forces are valid also for an accomodation coefficient $a \ll 1$, if the average temperatures of the reflected molecules are the same for all components of the gas

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